Economic Analysis of a Continuous Casein Process Using Carbon Dioxide as Precipitant[1]

ABSTRACT

Economic analyses are presented for two conceptual casein plants of commercial scale. For the first analysis, costs were estimated for a plant that used CO_2 as precipitant to manufacture casein. The results were compared with estimated costs for Ca caseinate plants. In the second analysis, costs were estimated for the precipitation step only for a casein plant that used CO_2 as a precipitant.

In the first case, the equipment was sized for a Ca caseinate plant with a flow rate of 10,000 L of milk/h and a caseinate output of 320 kg/h. Unit operating costs for production of CO_2-precipitated casein with recycling of CO_2 were \$0.038/kg less than for Ca caseinate manufactured from fresh casein and \$0.103/kg less than for casein manufactured from dried casein.

In the second case, operating costs for precipitation of casein with CO_2 in a plant with a flow rate of 50,000 L of milk/h and a casein output of 1500 kg/h are \$0.095/kg more than with lactic acid or HCl if CO_2 was not recycled. If CO_2 was recycled, capital costs were increased, but operating costs were significantly reduced. With recycling of CO_2, the cost difference between CO_2-precipitated casein and the other caseins was \$0.021/kg.

(**Key words**: economic analysis, carbon dioxide, casein, precipitation)

Abbreviation key: **CPC** = CO_2-precipitated casein.

INTRODUCTION

Commercially, casein is isolated from milk through the action of lactic acid-producing bacteria or through the addition of an acid such as HCl. The use of CO_2 to precipitate casein from milk has recently been demonstrated on a batch scale (9) and for a continuous pilot plant process (7, 8). There are many advantages to using CO_2 as a precipitant. The precipitant is eliminated from the whey upon release of pressure, unlike precipitation processes that use organic solvents or salts, and does not contaminate the curd. Neutralization of acids in the whey, which introduces salts, is generally unnecessary because the pH after precipitation is 6.0. This process produces a casein with a Ca content of approximately 1.5%, which is about the same as the Ca content of Ca caseinate prepared by addition of $Ca(OH)_2$ to casein.

The precipitation process for CO_2-precipitated casein (**CPC**) optimally takes place at temperatures from 38 to 43°C and pressures of 4140 to 6900 kPa (9). Higher pressures were not investigated because of pressure limitations of the equipment. Batch or semicontinuous processing for large quantities of casein is uneconomical because of the turnaround time required to fill the vessel with milk, pressurize the vessel with CO_2, heat and hold the vessel contents, depressurize the vessel, remove the casein and whey, clean the vessel, and then recharge the vessel for the next run. Turnaround time for batch processing is approximately 1 h for a 1-L batch. The continuous process (7, 8) by which milk and CO_2 were fed to a high pressure precipitator-reactor while casein was continuously removed from the reactor eliminates turnaround time. The methodology using the specified equipment may be used for other precipitation reactions or in supercritical extraction processes for reactor or extractor pressures up to 17,000 kPa.

It was the purpose of this study to conduct an economic analysis of the continuous precipitation of casein with CO_2 and to demonstrate that processing with high pressure CO_2 is an economic alternative to using acids.

Two cases were examined. In the first, costs were estimated for a plant that uses CO_2 to manufacture casein with a Ca content of approximately 1.5%. Costs were compared with estimated costs for plants that manufacture Ca caseinate. The Ca caseinate process was chosen for comparison because of its small market size. In the second case, costs for the continuous precipitation of casein with CO_2 were compared with costs encountered in the precipitation steps for production of mineral acid and lactic caseins, which are manufactured on a much larger scale than Ca caseinate.

We do not mean to suggest that the CPC process is a replacement for the Ca caseinate or casein processes. However, by comparing the CPC process to conventional casein processes, we intend to dispute the idea that processing with high pressure CO_2 is much more expensive than processing with acids.

MATERIALS AND METHODS

Equipment costs were obtained from equipment manufacturers, the Chemcost™ Program (Chemstations, Houston, TX) a software program for capital cost and profitability analysis; Aspen Plus™ (Aspen Technology, Inc., Cambridge, MA), a simulation and cost software program; and other in-house sources. Sanitary construction was assumed for all equipment. The remaining capital costs were estimated by Lang-type cost factors (2) and included costs for equipment installation, site preparation and improvement, concrete, building and structural steel, piping, electrical needs, instrumentation, insulation and painting, engineering and construction management, and contingency allowances. The cost factors can vary over a wide range with multipliers from less than 2 to multipliers of more than 6 (2) but are usually based on the characteristics of the equipment purchases. In this study, a factor of 2 was assumed. Maintenance and overhead costs were not included.

Operating costs included the costs of utilities, raw materials, labor, and capital depreciation. Because the economic analysis performed in this study is comparative in nature, costs associated with milk delivery, price of milk, and preprocessing of milk were not included. Preprocessing included milk storage at 3°C, skimming fat, pasteurization, and pumping. Costs associated with whey processing were not considered, although whey costs for the CO_2 process would likely be slightly less. In addition, costs associated with storage, packaging, and packaging materials were not included because they were considered to be the same in each process.

Total utility costs included the prices of electric power, natural gas, steam, and water. The cost of electric power was assumed to be \$0.05/kWh and of natural gas was assumed to be \$190/10^3 m^3. Electrical usage was calculated based on consumption by the motor drives. The price of steam was estimated at \$11.00/10^3 kg. The cost of water for washing or cooling was assumed to be \$700/10^6 m^3.

The prices of the raw materials were obtained from local vendors. The price of $Ca(OH)_2$ was quoted as \$240/10^3 kg. The price of 36% HCl was quoted as \$121/10^3 kg. In the US market, CO_2 prices may range from \$40 to \$300/10^3 kg delivered. Wholesalers pay 7 to 50% of the average \$77/10^3 kg (5). In this study, a price of \$66/10^3 kg was used.

The manufacturing processes described for both cases were assumed to be continuous and fully automated. Operating labor costs were assumed to be equal for all the processes and are not detailed unless specific for one process. Labor costs were assumed at \$10/h with 60% indirect labor costs. Indirect labor costs for each employee included social security, sick leave, vacation leave, taxes, and additional benefits.

Capital depreciation was calculated as 0.10 of the total capital investment assuming an economic life of 10 yr with straight-line depreciation.

ECONOMICS OF THE PROCESSES

Case 1. The Ca Caseinate and CPC Processes

Equipment design and plant costs. The Ca caseinate plants used as the basis for the cost studies were assumed to operate 24 h/d, 90% of a 365-d year, processing 10,000 L of milk/h (45 gal/min) with a caseinate output of 320 kg/h (700 lb/h). Calcium caseinate was made from either fresh or dried casein. Casein losses from washing or other processing steps were not considered in this analysis. Plant capacity was selected based on the suggestions obtained from discussions with local processors. As discussed previously, costs for preprocessing were not considered because those costs were approximately the same for the three processes.

After fat is skimmed from the milk and milk is pasteurized, casein manufacture usually consists of precipitation steps with curd formation, separation of the curd from the whey, curd washing steps, curd pressing, drying, tempering, milling, sieving, blending, bagging, and storage (6). Casein is precipitated using a mineral acid such as HCl or lactic acid-producing bacteria. Regardless of the precipitant used, the steps following precipitation are essentially the same for both processes.

For preparation of Ca caseinate from fresh casein, the steps following curd pressing are omitted, and the curd is milled and then mixed with water. This step is followed by milling, addition of $Ca(OH)_2$, and drying. Some processors neglect the washing and curd pressing steps. Preparation of Ca caseinate from dried casein is essentially the same as preparation from the fresh curd.

Ca Caseinate production from fresh casein. In the analysis that follows, milk was assumed to have entered the process at 3°C and precipitation of casein to have taken place at 45°C. Coagulation temperatures of 40 to 45°C are used commercially (1). The process flow sheet for the production of fresh or dried casein and Ca caseinate is shown in Figure 1. Addition of water to the process vessels is not shown in the figure. Equipment costs are given in Table 1. Total utility costs for steam, natural gas, electrical consumption, and water are shown in Table 2.

An HCl storage tank was sized for a capacity of about 38,000 L (10,000 gal), ensuring a 30-d supply. The tank was fed with a 36% (wt/wt) aqueous solution of HCl from an unloading station equipped with a 5-hp centrifugal pump operating at 400 L/min (100 gal/min) at delivery. A 600-L (150 gal) dilution tank was sized for an operating capacity of 1 h and was fed by a 0.5-hp reciprocating pump delivering approximately 55 kg/h (120 lb/h) of the HCl solution from storage. Water was also fed into the tank at the rate of 8.3 L/min (2.2 gal/min). An HCl concentration of 1*N* was used. A 0.5-hp reciprocating pump was used to inject the acid into milk at a rate of 10 L/min (2.5 gal/min) to a static mixer, represented by the acid and milk mixing chamber. Milk was pumped to the static mixer at the rate of 45 gal/min. The cost of pumping milk to the process was assumed to be part of milk handling and preparation. Steam was then injected into the acid-milk mixture to raise its temperature to 45°C. Two additional 0.5-hp reciprocating pumps are included in the costs of Table 1 as spares. The acidulation pipeline was assumed to be a length of pipe equipped with a tee for steam injection. The costs for the acid-milk mixing chamber were estimated and included costs for piping, fitting, valves, and instrumentation.

After precipitation, the casein and whey were separated using a dewatering drum equipped with a 5-hp hydraulic unit. The curd and whey flowed into

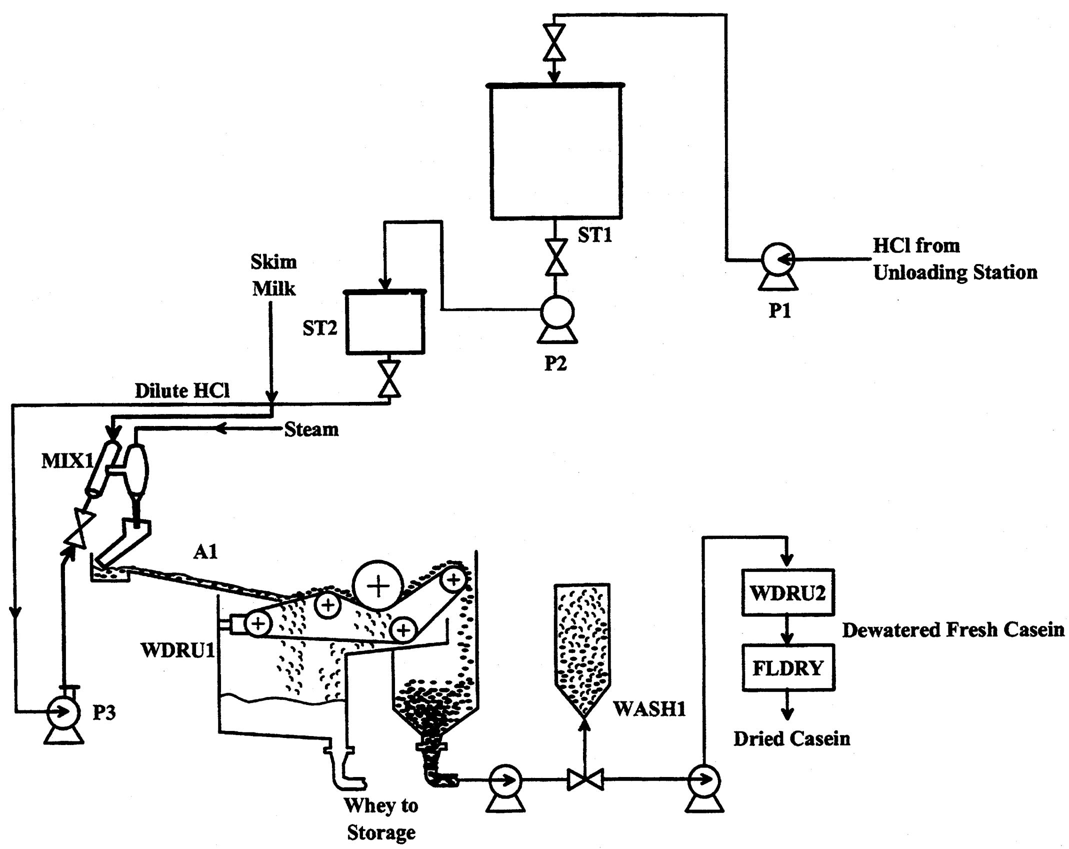

Figure 1. Schematic diagram of a casein processing plant (1). P1 = Pump, ST1 = HCl storage tank, P2 = pump, ST2 = dilution tank, P3 = pump, MIX1 = acid-milk mixing chamber, A1 = acidulation pipeline with steam injection, WDRU1 = dewatering drum, WASH1 = tower washer for casein, WDRU2 = dewatering drum, and FLDRY = fluid-bed dryer.

the collection vessel of the Rietz whey drainer (Bepex Corporation, Santa Rosa, CA). The casein-whey slurry overflowed onto the belt of the drum, and the whey drained into storage. The curd was pressed between the belt and the drum, and the curd dropped into a discharge chamber. Reclaimed water was used to cool the curd. The curd was then pumped to a vertical washing tower using a positive displacement pump. The cost of the pump was included in the cost of the dewatering drum. It was assumed that the casein was then washed in a 19,000-L (5000-gal) Rietz vertical tank tower washer (Bepex Corporation, Santa Rosa, CA), followed by pressing in a second dewatering drum. The vertical tank tower washer displaced the water carried from the dewatering drum with fresh water. The second dewatering drum was similar to the first dewatering drum in size and operation. The cost of a positive displacement pump was included with the second dewatering drum. At this stage, 320 kg/h (700 lb/h) of casein, on a dry basis, were produced, or approximately 710 kg/h (1600 lb/h) of casein if a moisture content of 55% was assumed after dewatering.

Steps depicting the conversion of casein to Ca caseinate are shown in Figure 2 and generally follow those outlined by Roeper (4). Prior to the addition of $Ca(OH)_2$, fresh casein was milled to reduce the curd to approximately 0.7 cm. About 710 kg/h (1600 lb/h) of casein and about 550 kg/h (1200 lb/h) of water were fed to a 200-L (50-gal) jacketed mixing tank that was equipped with an agitator. The vessel contents were held for approximately 6 min at 35 to 40°C and then pumped to a colloid mill. The colloid mill was an in-line emulsifier type set at 150 μ. The casein

TABLE 1. Equipment costs for production of casein and Ca caseinate at a milk input of 10,000 L/h (45 gal/min).

Section	Identification	Description	Cost
			($)
Milk handling and preparation			NI[1]
Acid handling		Unloading station.	
	P1	Centrifugal pump 400 L/min (100 gal/min). Occasional operation.	7000
	ST1	HCl Storage tank 38,000-L (10,000 gal). Tank material is dual-lined plastic.	35,000
	P2	Acid-reciprocating pump (n = 2).[2] One spare 0.8 L/min (0.2 gal/min).	7000
	ST2	Dilution tank, 600-L (150 gal).	5000
	P3	Acid injection reciprocating pump (n = 2). One spare.	6000
Precipitation	MIX1	Acid/milk mixing chamber.	10,000
	A1	Acidulation pipeline with steam injection.	4000
Whey separation	WDRU1	Woven plastic mesh belt with dewatering drum and pump. Rietz[3] curd drainer.	80,000
Casein curd washing	WASH1	Tower washer 19,000 L (5000-gal vertical tank) Rietz[3] washer-cooler.	40,000
Casein curd pressing	WDRU2	Woven plastic mesh belt with dewatering drum and pump. Rietz[3] curd drainer.	80,000
Casein curd drying	FLDRY	Fluid-bed dryer.	250,000
Milling	MIL1	Cone mill.	25,000
Casein-water mixing	ST3	Tank 200-L (50 gal).	4000
		Agitator.	2000
	P4	Pump.	3000
Colloid mill	MIL2	In-line emulsifier mixer.	13,000
Addition of $Ca(OH)_2$	HOP1	$Ca(OH)_2$ Bag breaker and storage hopper.	9000
	MET1	$Ca(OH)_2$ Powder meter.	5000
	ST4	$Ca(OH)_2$ Water-powder mix tank 200-L (50 gal).	4000
		Agitator.	2000
	P5	$Ca(OH)_2$ solution pump.	3000
	ST5	$Ca(OH)_2$-casein dissolving tank. 400-L (100 gal) jacketed vessel.	5000
		Agitator.	2000
Drying			
	HEX1	Heat exchanger.	10,000
	SPDRY	Spray-dryer.	659,000
Packaging line			NI
Storage			NI

[1]Not included.

[2]Number of units is given in parentheses; otherwise, 1 unit.

[3]Bepex Corporation (Santa Rosa, CA).

TABLE 2. Summary of economic analysis for the production of Ca caseinate from dried casein or fresh casein and production of CO_2-precipitated casein with 97% CO_2 recycle or 0% recycle of CO_2.

Item	Dried casein	Fresh casein	With 97% CO_2 recycle	With 0% CO_2 recycle
	($)			
Equipment costs	1,270,000	1,020,000	1,147,000	1,022,000
Additional capital costs	2,540,000	2,040,000	2,294,000	2,044,000
Capital costs	3,810,000	3,060,000	3,441,000	3,066,000
Operating costs	901,000	739,000	642,000	872,000
Utilities				
Steam	141,000	76,000	64,000	64,000
Natural gas	114,000	114,000	114,000	114,000
Electricity[1]	59,400	38,000	109,700	82,700
Water	8800	8800	5000	5000
Raw materials				
Milk	NI[2]	NI	NI	NI
$Ca(OH)_2$	18,200	18,200		
HCl	52,000	52,000		
CO_2				300,000
Fresh CO_2			5000	
Labor (1 person)	126,100	126,100		
Capital depreciation	381,000	306,000	344,100	306,600
Unit operating costs[3]				
$/kg	0.358	0.293	0.255	0.346
$/lb	0.163	0.133	0.116	0.157

[1]Includes an additional 20% over equipment electrical costs for miscellaneous expenses.

[2]Not included.

[3]Plant caseinate output = 2,520,000 kg/yr (5,540,000 lb/yr).

solution was then mixed with $Ca(OH)_2$ in a 400-L (100-gal) mixing tank to produce Ca caseinate.

A $Ca(OH)_2$ bag breaker and storage hopper with a 5-d capacity (about 1080 kg or 2400 lb) was assumed. The $Ca(OH)_2$ was metered at a rate of 9 kg/h (20 lb/h) to an agitating 200-L (50-gal) mixing tank, where the $Ca(OH)_2$ was mixed with about 80 kg/h (180 lb/h) of water and held for about 30 min. The $Ca(OH)_2$ solution was then pumped to a 400-L (100-gal) jacketed vessel where it was mixed with the milled casein solution. The vessel contents were agitated and held for about 10 min at 35 to 40°C.

The operating labor costs that were associated with $Ca(OH)_2$ handling are not part of the CPC process. Labor is required to load the $Ca(OH)_2$ to the hopper. One full-time operator, working 24 h/d, was assumed.

The Ca caseinate slurry, about 24% (wt/wt), was then heated from 35 to 70°C in a double-pipe heat exchanger with an area of 3 m^2 (33 ft^2) as determined using the Aspen Plus™ software and dried in a spray-dryer. The heating medium was steam. About 320 kg/h (700 lb/h) of Ca caseinate with a 3% moisture content was produced.

Equipment costs are summed in Table 2. Total equipment costs were $1,020,000. Additional capital costs were $2,040,000. Total capital costs were $3,060,000. Annual utility costs were $236,800 and are detailed in Table 2. Operating costs of $739,000 were also included and are the sum of the costs of utilities, raw materials, labor, and capital depreciation. Based on a production rate of 320 kg/h (700 lb/h) and a production schedule at 90% utilization, the annual production rate of Ca caseinate was 2,520,000 kg (5,540,000 lb). Operating costs were $0.293/kg ($0.133/lb) of product.

Ca Caseinate production from dried casein. The steps for production of Ca caseinate from dried casein were similar to those described for processing from fresh curd, except that additional capital and utilities costs are incurred because of the cost of the drying equipment (Figure 1).

After pressing, the curd was dried in a fluidized-bed dryer, and moisture content was lowered from 30 to 35% in the first stage and from 5 to 12% in the second stage. The casein leaving the dryer was assumed to have a moisture content of 8%. The curd was then mixed with $Ca(OH)_2$ as described, to produce Ca caseinate.

The equipment costs for this case were $1,270,000. Additional capital costs were $2,540,000. Total capital costs were $3,810,000. Total operating costs of $901,000 are detailed in Table 2. Based on the same annual production rate given above for fresh casein, the operating costs for production of Ca caseinate from dried casein were $0.358/kg ($0.163/lb).

Preparation of CPC. A flow sheet for a proposed commercial process for casein precipitation using CO_2 is shown in Figure 3, and the equipment is described in Table 3. Two variations of the process are discussed: 1) almost all of the CO_2 is recovered and recycled, and 2) none of the CO_2 used in precipitation is recovered.

The costs associated with liquid CO_2 included the storage system and refrigeration system. A high pressure pump was required to pump milk at 4°C from atmospheric pressure to the line pressure of 6900 kPa at the rate of approximately 10,000 L/h (45 gal/min). The large capacity pump and the high operating pressure required a motor drive of 80 hp. The CO_2, maintained at –18°C, was pumped from the storage pressure of 2070 kPa to the line pressure. The pump fed 4 kg of CO_2/100 kg of milk (9). In the second mixing chamber, a static mixer ensured good contact between the milk and CO_2 streams. Following Tomasula (7) and Tomasula et al. (8), a double-pipe heat exchanger was used to heat milk rapidly from 3 to 38°C. A residence time of 0.5 min was assumed.

After precipitation and formation of the curd, the casein, whey, and CO_2 moved through a progressing cavity pump for reduction to atmospheric pressure. The pump had a capacity of 170 L/min (45 gal/min). The estimated price for a 27 L/min (70 gal/min) pump at 6900 kPa was $75,000.

Up to 415 kg/h (900 lb/h) of CO_2 could be recovered from the whey after precipitation. The whey was filtered to clean the gas. The gas was compressed to 2070 kPa and then dried and cooled from 38 to –14°C. Fresh or makeup CO_2 in the amount of 0.1 kg CO_2/100 kg milk was added to the compressed CO_2 to replace the CO_2 that was not recovered. Whey was separated from the casein as was described for Ca caseinate from fresh curd (Table 1 and Figure 1). However, the dewatering drums and tower washer were smaller because less water was carried through the process after the precipitation step than during precipitation with HCl. The equipment leading to drying of the CPC was assumed to be identical to that shown in Table 1 and Figure 1.

Capital and operating costs for production of CPC with 97% recycling of CO_2 are given in Table 2. Equipment costs were $1,147,000. Additional capital costs were $2,294,000. Total capital costs were $3,441,000. Total operating costs were $642,000.

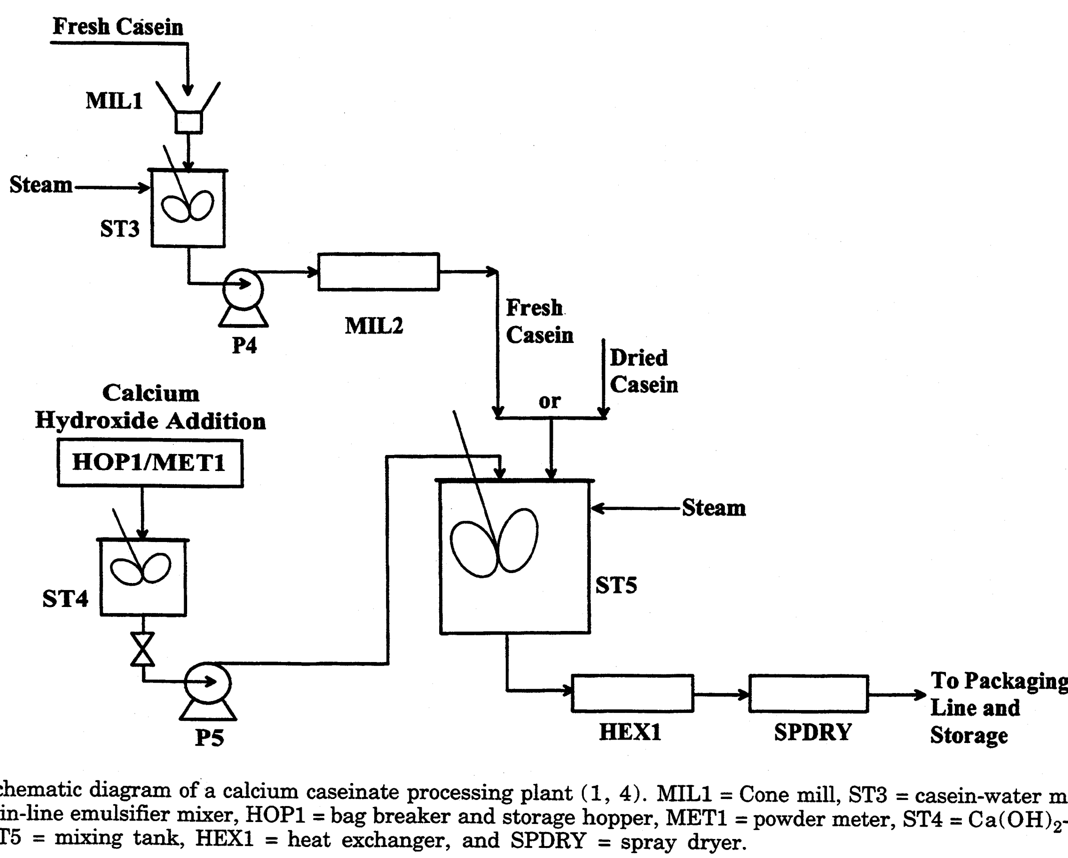

Figure 2. Schematic diagram of a calcium caseinate processing plant (1, 4). MIL1 = Cone mill, ST3 = casein-water mixing tank, P4 = pump, MIL2 = in-line emulsifier mixer, HOP1 = bag breaker and storage hopper, MET1 = powder meter, ST4 = $Ca(OH)_2$-water mix tank, P5 = pump, ST5 = mixing tank, HEX1 = heat exchanger, and SPDRY = spray dryer.

Based on an annual production rate of 2,520,000 kg/yr (5,500,000 lb/yr), the operating costs for production of CPC were \$0.255/kg (\$0.116/lb).

If CO_2 is not recycled after casein precipitation, capital costs were reduced to \$3,066,000 because the CO_2 recovery equipment was not required. Total operating costs, however, increase to \$872,000 because 4 kg of CO_2/100 kg of milk must be added to the process instead of 0.1 kg of CO_2/100 kg of milk when CO_2 is recovered. For an annual production rate of 2,520,000 kg of casein, the operating costs were \$0.346/kg (\$0.157/lb).

Cost comparison of processes. A comparison of the equipment costs of Table 2 for the two CPC processes shows that the capital costs for CPC with 97% recovery and recycling of CO_2 were higher than those for the same process with 0% recovery of CO_2. The higher costs were due to the additional equipment required for recovery of CO_2. Capital costs for the CPC process with 97% CO_2 recovery were higher than those for the Ca caseinate process from fresh casein because of the prices of the high pressure pumps as well as the recovery equipment. However, there were comparative cost savings because the dewatering equipment for the CPC process was of smaller scale.

The unit operating costs for production of CPC with a recycle of 97% of CO_2 were less than those of all the other processes (Table 2). The higher operating costs for production of CPC without recovery of CO_2 were due to the price of CO_2 (\$300,000) compared with the price of fresh or makeup CO_2 (\$5000) if most of the CO_2 is recovered. A comparison with production of Ca caseinate from either dried or fresh casein shows that additional operating costs for these processes were incurred because of the additional operating labor

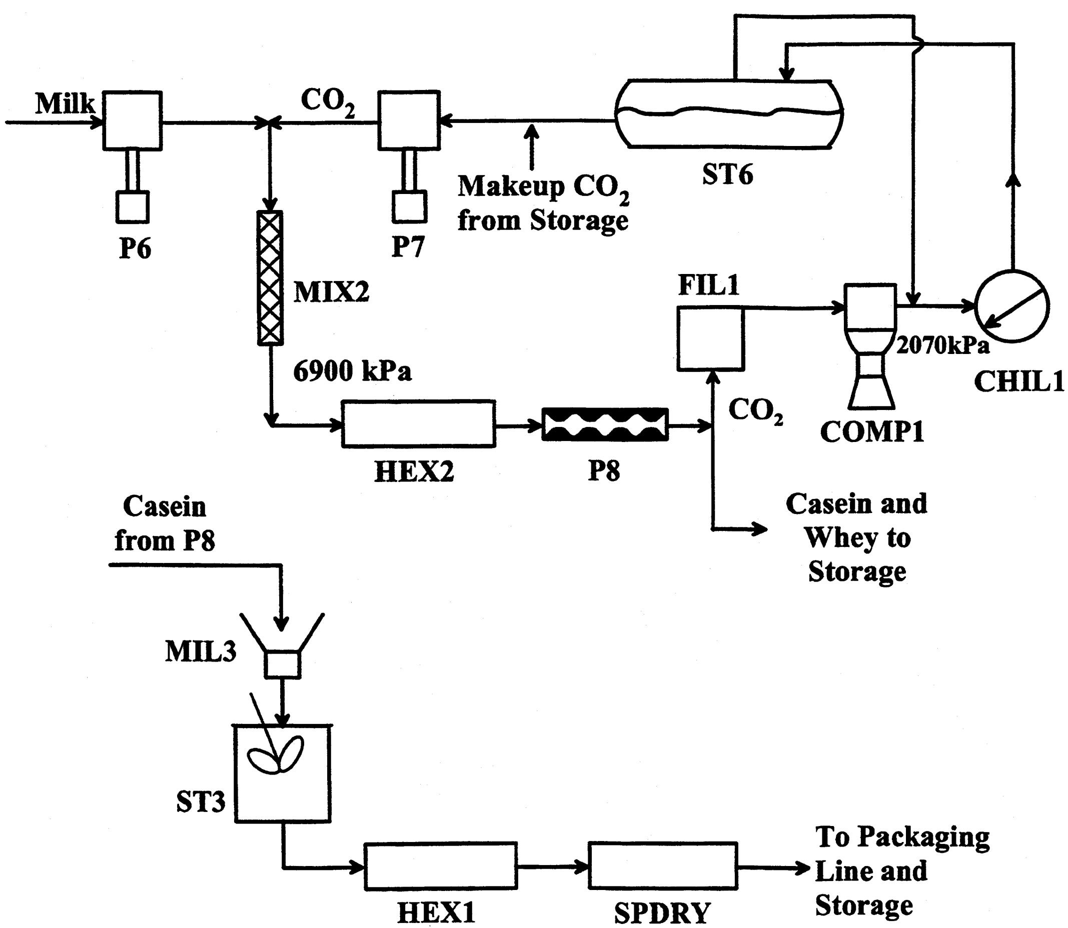

Figure 3. Schematic diagram of a proposed CO_2-precipitated casein processing plant. Dewatering, and washing, and pressing of casein following P8 not shown in the figure. P6 = High-pressure pump, ST6 = CO_2 mix tank, P7 = CO_2 pump, MIX2 = mixing chamber, HEX2 = heat exchanger, P8 = progressing cavity pump, FIL1 = CO_2 filter, COMP1 = CO_2 compressor, CHIL1 = CO_2 chiller, MIL3 = cone mill, ST3 = tank, HEX1 = heat exchanger, and SPDRY = spray dryer.

requirements associated with $Ca(OH)_2$ handling as well as the additional utilities costs in the case of production of Ca caseinate from dried casein.

An analysis of return on investment (2) was used to compare the economics of the CPC process with recovery of CO_2 with the process using Ca caseinate from fresh casein. An economic life of 10 yr was assumed with straight-line depreciation and a tax rate of 33%. The results are reported in Table 4. The capital costs for the CPC process are $381,000 more than that for the Ca caseinate process. However, the savings in operating costs with the CO_2 process are $139,359 for the initial year, assuming an annual escalation of 3%. (Only the increase in annual costs is given in the table.) The incremental return on investment is approximately 27%.

Case 2. Precipitation Stages

Equipment design and cost. The cost analysis is performed only for the precipitation stages of the three processes and demonstrates the costs incurred when the CO_2 process is used in large-scale processing. The costs associated with the preprocessing of milk are not included in this analysis because they are assumed to be the same for the three processes. The steps following the precipitation stage are assumed to be the same for all processes.

The casein plant used as the basis for the cost studies was assumed to operate 24 h/d, 90% of a 365-d-year, and to process 50,000 L of milk/h (220 gal/min) with a casein output of 1500 kg/h (3300 lb/h). The size of the plant was based on a facility in the midpoint range of casein plants as described by Caric (1). Operating labor costs were assumed to be equal for the three continuous, fully automated processes and are not detailed.

Lactic casein precipitation. Lactic casein manufacture has been discussed by Caric (1). The lactic starter system was sized based on information given by Nicolaus (3) and is shown in Figure 4.

TABLE 3. Equipment costs for production of CO_2-precipitated casein at a milk input of 10,000 L/h (45 gal/min).

Section	Identification	Description	Cost
			($)
Milk handling and preparation			NI[1]
	P6	High pressure pump, Rannie[2] Pump	95,000
CO_2 Handling		Liquid CO_2 storage system including refrigeration	W/CO_2[3]
	ST6	Feed and recycle mix tank, pressure rating = 2070 kPa (300 psig), with cooling system	10,000
	P7	CO_2 pump	10,000
Precipitation			
	MIX2	Mixing chamber	4000
	HEX2	Heat exchanger	6000
	P8	Progressing cavity pump 170 L/min (45 gal/min)	75,000
	FIL1	CO_2 Filter	10,000
	COMP1	CO_2 Compressor	95,000
	CHIL1	CO_2 Chiller	10,000
Whey separation			
	WDRU1	Woven plastic mesh belt with dewatering drum	53,000
Curd washing	WASH1	Tower washer	26,000
Curd pressing	WDRU2	Woven plastic mesh belt with dewatering drum	53,000
Milling	MIL3	Cone-mill	25,000
Mixing	ST3	Tank	4000
		Agitator	2000
Drying	HEX1	Heat exchanger	10,000
	SPDRY	Spray dryer	659,000
Packaging line			NI[1]
Storage			NI[1]

[1]Not included.

[2]APV Rannie, Inc. (St. Paul, MN).

[3]Costs included with the cost of CO_2.

TABLE 4. Relative economics of CO_2-precipitated casein and Ca caseinate produced from fresh casein.

	CO_2-Precipitated casein process	Ca Caseinate process
	($)	
Capital costs	3,441,000	3,060,000
Annual operating costs		
Utilities	292,700	236,800
Other raw materials	5000	70,200
Other operating costs Incremental labor	0	126,000
Total operating costs (excluding depreciation)	297,700	433,000
Comparison of processes		
Increase in capital cost	381,000	
Increase in annual costs yr 1	(135,300)[1]	
Increase in annual depreciation	38,100	
Incremental return on investment, %	27	

[1]Parenthesis indicates a negative value.

Eight coagulation tanks (only two are shown in the figure) of approximately 100,000-L (26,400-gal) capacity each were sized based on a flow rate of 50,000 L of milk/h (220 gal/min) and a holding time of 17 h. The vessels were assumed to be large, vertical silo-type vessels. Milk was assumed to enter the coagulation tanks at 3°C, and curd acidulation was assumed to take place at 52°C. The acidulation pipeline through which the curd passes was assumed to consist of a steam injector and a holding tube for agglomeration of the curd.

The equipment costs for the feed pump, eight coagulation tanks, the lactic starter system, the acidulation pipeline pump, and the acidulation pipeline are given in Table 5. The cost of the lactic starter system included an estimate of 100% for additional capacity and was escalated to current day costs. The subtotal of equipment costs was \$534,000. Additional capital costs were \$1,068,000. The total estimated capital cost for the lactic casein system was \$1,602,000.

The total annual operating cost for the lactic casein precipitation step was \$293,000 (Table 6). Steam costs represented most of the utility costs at \$107,000. It was assumed that heat balancing was done in the lactic casein facility and that 50% of the heat in the process stream was recovered and reused. For an annual production rate of 11,460,000 kg/yr of casein, the unit operating costs for the precipitation step were \$0.026/kg (\$0.012/lb).

Precipitation with HCl. The casein precipitation process has already been shown in Figure 1. Equipment costs for the precipitation step only are given in Table 7. Two HCl storage tanks were sized for a capacity of about 90,000 L (24,000 gal) ensuring a 30-d supply. The tanks were fed with a 5-hp centrifugal pump operating at 400 L/min (100 gal/min). A dilution tank of 6000 L (1600 gal) was sized for an operating capacity of 1 h. A static mixer was used to represent the acid-milk mixing chamber. The acidulation pipeline was assumed to be similar to that used in the smaller scale plant. As in the lactic casein process, milk was assumed to have entered the process at 3°C. Coagulation took place at 45°C.

Total equipment costs were \$143,900, and additional capital costs were \$287,800. Total operating costs were \$294,000/yr (Table 6). Based on the annual production rate of casein of 11,460,000 kg/yr, unit costs were \$0.026/kg (\$0.012/lb).

CPC with no recovery of CO_2. Referring to Figure 3 for the CPC process, two high pressure Rannie pumps (instead of the one pictured for the smaller system) were required to pump milk from atmospheric pressure to the line pressure of 6900 kPa for a total flow rate of 50,000 L/h (220 gal/min). Equipment costs are listed in Table 8 but do not include the filter, compressor, chiller, or the CO_2 feed and recycle mix tank. The large capacity pumps, oper-

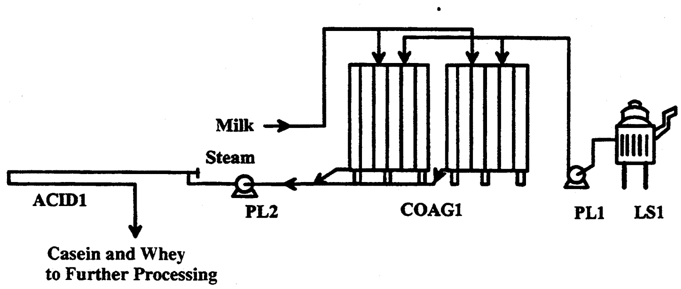

Figure 4. Schematic diagram of a lactic casein processing plant (1). Eight coagulation tanks were assumed for the process of this study. PL1 = Pump; COAG1 = coagulation tanks; LS1 = lactic starter system; PL2 = pump; and ACID1 = acidulation pipeline with steam injection.

TABLE 5. Equipment costs for the precipitation step in lactic casein production.

Identification	Description	Cost
		($)
PL1	Feed pump for the coagulation tanks	8000
COAG1	Coagulation tanks	480,000
LS1	Lactic starter system	28,000
PL2	Acidulation pipeline pump	8000
ACID1	Acidulation pipeline with steam injection	10,000

TABLE 6. Summary of economic analysis for the precipitation steps in the lactic casein and mineral casein facilities and for production of CO_2-precipitated casein with and without recycle of CO_2 and milk input of 50,000 L/h (220 gal/min).

Item	Lactic casein precipitation	Mineral casein precipitation	With 97% CO_2 recycle	With 0% CO_2 recycle
	($)			
Equipment costs	534,000	143,900	792,000	476,000
Additional capital costs	1,068,000	287,000	1,584,000	952,000
Capital costs	1,602,000	432,000	2,376,000	1,428,000
Operating costs[3]	293,000	294,000	534,000	1,392,000
Utilities				
Steam	107,000	103,000	78,000	78,000
Electricity[1]	26,000	3000	192,000	162,000
Water			1000	1000
Raw materials				
HCl		145,000		
CO_2			25,000	1,008,000
Capital depreciation, 10-yr write off	160,200	43,200	238,000	143,000
Unit operating costs[2]				
$/kg	0.026	0.026	0.047	0.121
$/lb	0.012	0.012	0.021	0.055

[1]Includes an additional 20% over equipment electrical costs for miscellaneous expenses.

[2]Plant casein output = 11,460,000 kg/yr (25,210,000 lb/yr).

[3]Labor costs assumed equal.

ating under high pressure, require motor drives of 200 hp each. One CO_2 pump with a capacity of 34 L/min (9 gal/min) was required to pump CO_2 from storage pressure of 2070 kPa (300 psi) to line pressure. The pump fed 4 kg of CO_2/100 kg of milk to the static mixer. A double-pipe heat exchanger was designed using Aspen Plus™ to bring milk from 3 to 38°C. A residence time of 0.5 min was assumed.

The mixture of casein, whey, and CO_2, consisting of 6500 kg/h (14,300 lb/h) casein on a wet basis and 2500 kg/h (5500 lb/h) whey was passed to a progressing cavity pump for reduction to atmospheric conditions and further processing.

Total equipment costs were $476,000 with additional capital costs of $952,000. Total capital costs were $1,428,000.

Annual operating costs are shown in Table 6. The cost of CO_2 was over 70% of the operating costs at $1,008,000. Total operating costs were $1,392,000. Unit costs, based on a production rate of 11,460,000 kg/yr, were $0.121/kg ($0.055/lb).

CPC with 97.5% recycle of CO_2. Equipment costs are listed in Table 8. In this case, CO_2 was recovered after pressure reduction. Capital costs were increased compared with the previous case because of the costs for the filter, compressor, chiller, and the mix tank. Total capital costs, as listed in Table 6, were $2,376,000.

Operating costs were $534,000 (Table 6). Increases in utility costs from the previous case were because of the electricity costs associated with the compressor motor and chiller. Fresh or makeup CO_2 costs were reduced even further than the 0% recovery of CO_2 and amounted to only $25,000. Unit costs were $0.047/kg ($0.021/lb).

Cost comparisons of the precipitation steps. Higher capital costs encountered in CO_2 precipitation were due to the relatively high costs of pumping milk to this stage, pressure reduction, and CO_2 recovery and recycling (Tables 6 and 8). Capital costs for

TABLE 7. Equipment costs for the precipitation step in casein production.

Identification	Description	Cost
		($)
Unloading station		
P1	Centrifugal pump	6500
ST1	HCL storage tanks (n = 2)[1], 91,000 L (24,000 gal) each; 30-d supply	68,000
P2	Acid pump to the dilution tank	10,700
ST2	Dilution tank 5900-L (1550-gal) capacity	10,000
P3	Acid injection pump, reciprocating type	13,700
Precipitation		
MIX1	Acid-milk mixing chamber	25,000
A1	Acidulation pipeline with steam injection	10,000

[1]Number of units is given in parentheses; otherwise, 1 unit.

TABLE 8. Equipment costs for production of CO_2-precipitated casein.

Section	Identification	Description	Cost
			($)
Milk handling and preparation			NI[1]
	P6	High pressure pump (n = 2)[2]	326,000
CO_2 Handling		Liquid CO_2 storage system including refrigeration	W/CO_2[3]
	ST6	CO_2 feed and recycle mix tank	25,000
	P7	CO_2 high pressure pump	25,000
Precipitation			
	MIX2	Mixing chamber	10,000
	HEX2	Heat exchanger	15,000
	P8	Pressure reducing pump	100,000
	FIL1	CO_2 filter after progressing-cavity pump	25,000
	COMP1	CO_2 compressor	241,000
	CHIL1	CO_2 chiller	25,000

[1]Not included.

[2]Number of units are given in parentheses; otherwise 1 unit.

[3]Costs included with the cost of CO_2.

lactic casein precipitation were also relatively expensive because of the cost of the precipitation vessels (Table 5). Operating costs for the precipitation step in both CO_2 processes were more expensive than those of the lactic casein and casein plants because of the electrical costs associated with the large motor drives for the pumps. These costs were partially offset by the decreased steam usage in the CO_2 processes. Operating costs for the CPC with 0% recovery of CO_2 were highest because of the price of CO_2.

DISCUSSION

For case 1, the cost of manufacturing CPC was compared with the cost of manufacturing Ca caseinate in a small model plant. These processes were not compared to suggest CPC as a replacement for Ca caseinate but to show that the economics of a process using a high pressure gas can be economically competitive to one that does not. Operating costs for production of CPC with recovery of CO_2 were $0.038/kg less than operating costs for manufacture of Ca caseinate from fresh casein. The costs of making CPC are mainly due to the equipment costs for recovery and handling of CO_2 and the price of CO_2 itself. A sensitivity analysis was not performed for this case because it is obvious that, even with optimization for minimum costs for solvent recycling, utilities, and equipment, the price of CO_2 is always a significant fraction of the operating costs and the recovery equipment a significant fraction of the equipment costs. However, because less water is used in the CO_2 processes, equipment for dewatering and washing is smaller and consequently costs less. In addition, it may be possible to omit the washing stage in CPC processing as many processors already do for Ca caseinate processing. The calculations for return on investment, which are useful for comparing alternative processes, show that the CPC process is competitive.

For case 2, the cost of the precipitation stage only for the manufacture of CPC was compared with costs encountered in the precipitation stages for acid and lactic caseins. A larger model plant was used. This case pointed out a potential limitation of the use of high pressure CO_2 in large-scale processes at this time, which is the availability of large sanitary pumps to reduce pressure and to remove casein from the process continuously. Pumps with the capacity and pressure requirement specified in this study are not available off the shelf by manufacturers of progressing cavity pumps and would have to be made by special order. Smaller pumps arranged in parallel are a possibility as a replacement for one large pump, but may increase operating costs. Because only costs for the precipitation steps were compared in the larger scale processes, economic measures normally performed in an economic analysis, such as total annual manufacturing costs and profitability, were not performed.

CONCLUSIONS

Cost analyses have been presented for two conceptual commercial-scale plants that use CO_2 as a precipitant to manufacture casein with a Ca content of approximately 1.5%. In the first plant, the operating costs were compared with the costs to manufacture Ca caseinate in a plant of average capacity. Capital and operating costs using CO_2 as a precipitant were compared with the precipitation steps in the lactic casein and mineral casein processes in the second conceptual plant.

The CPC process is economical compared with the Ca caseinate process if CO_2 is recovered from the whey and recycled. The CPC process is not economical if CO_2 is not recycled because of the high price of CO_2. Equipment costs were more expensive than those of the Ca caseinate process because of the costs of the CO_2 recycling equipment and the costs of the high pressure pumps. However, dewatering and washing costs were less because CO_2 does not introduce water into the process with the precipitant. A comparison of the precipitation step for the larger conceptual plant that used CO_2 as a precipitant with the lactic casein and mineral casein precipitation steps showed that operating costs for the larger CO_2 plant were \$0.021/kg more expensive, mainly because of the higher utilities costs associated with operation of the high pressure pumps.

This study shows that processing using high pressure CO_2 on the scale described in this study is an economical alternative to using acids and disputes the idea that processing with high pressure CO_2 is significantly more expensive than processing with acids.